Reservoirs of Hot Gas in the IGM and Galactic Halo

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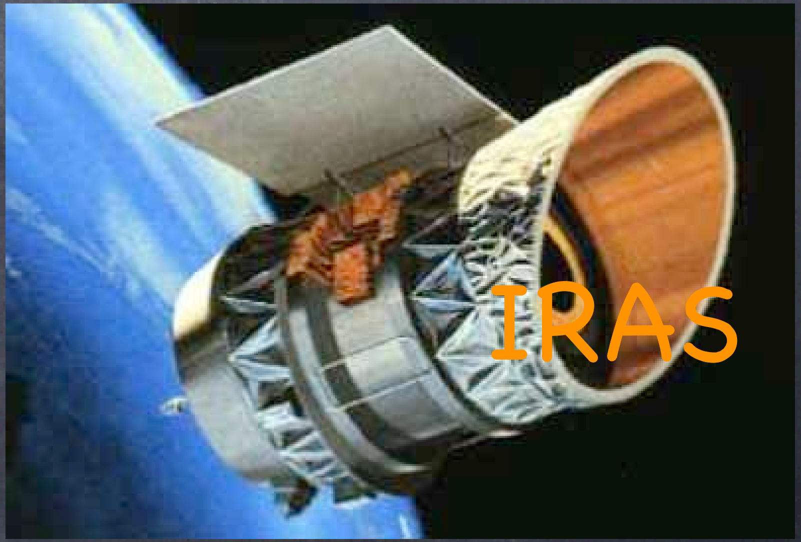


Outline of this Review

- *Major Reservoirs of Gas: The IGM and Halo*

- *The low-redshift IGM (≥40% of Ω_b)*

IGM Baryon and Metallicity Surveys

10% Z_{solar}
(in filaments)

<2% Z_{solar}
(in voids)

Absorber Distances to Galaxies

Metal-Transport Distances

200-800 kpc

- *Galactic High-Velocity Clouds*

Hot-Gas Cooling Time

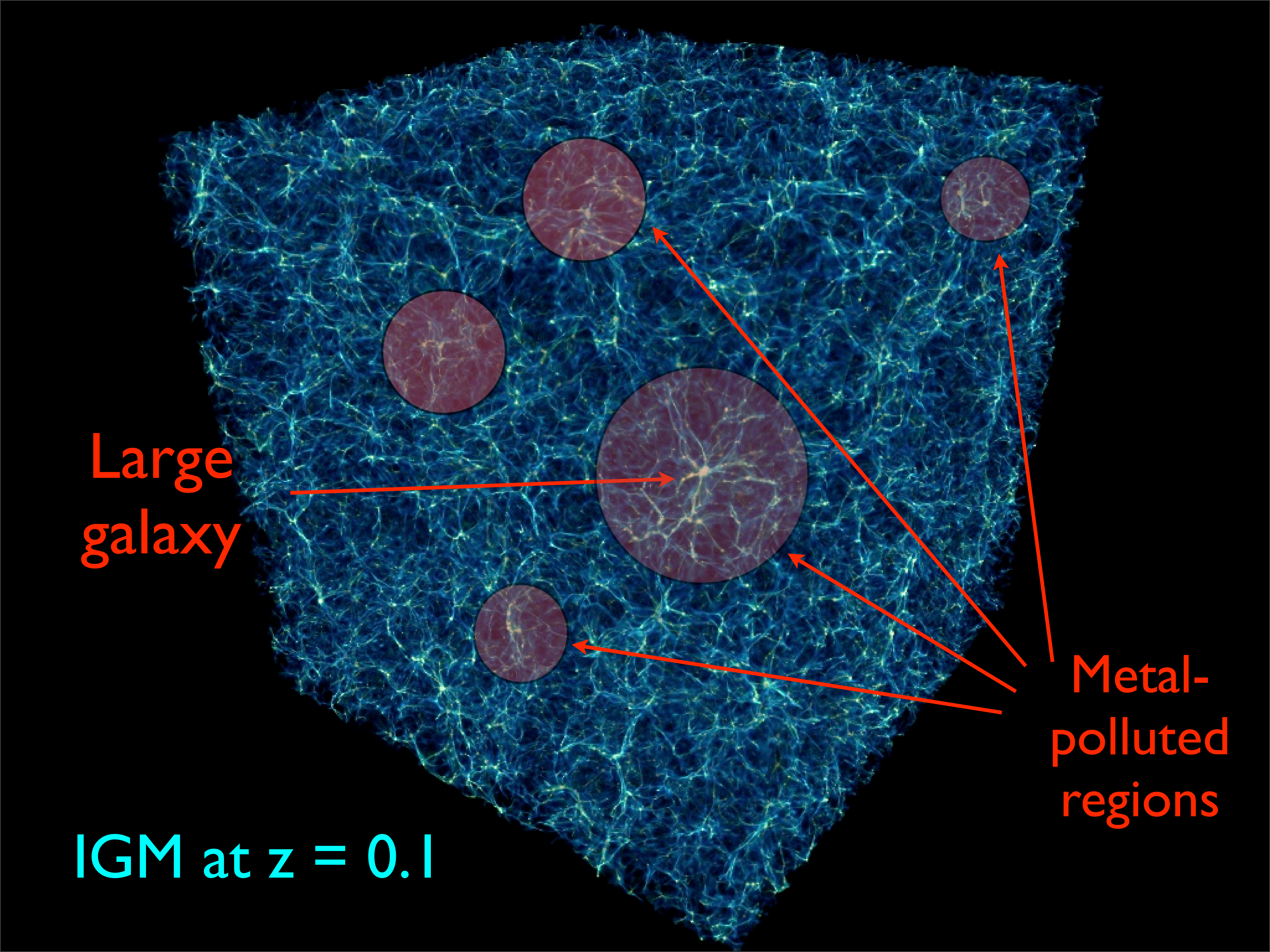
$t_{cool} \leq 2$ Gyr
($n > 10^{-4}$ cm^{-3} and $Z = 0.2$ solar)

Mass Infall Rate

0.1 M_{sun}/yr

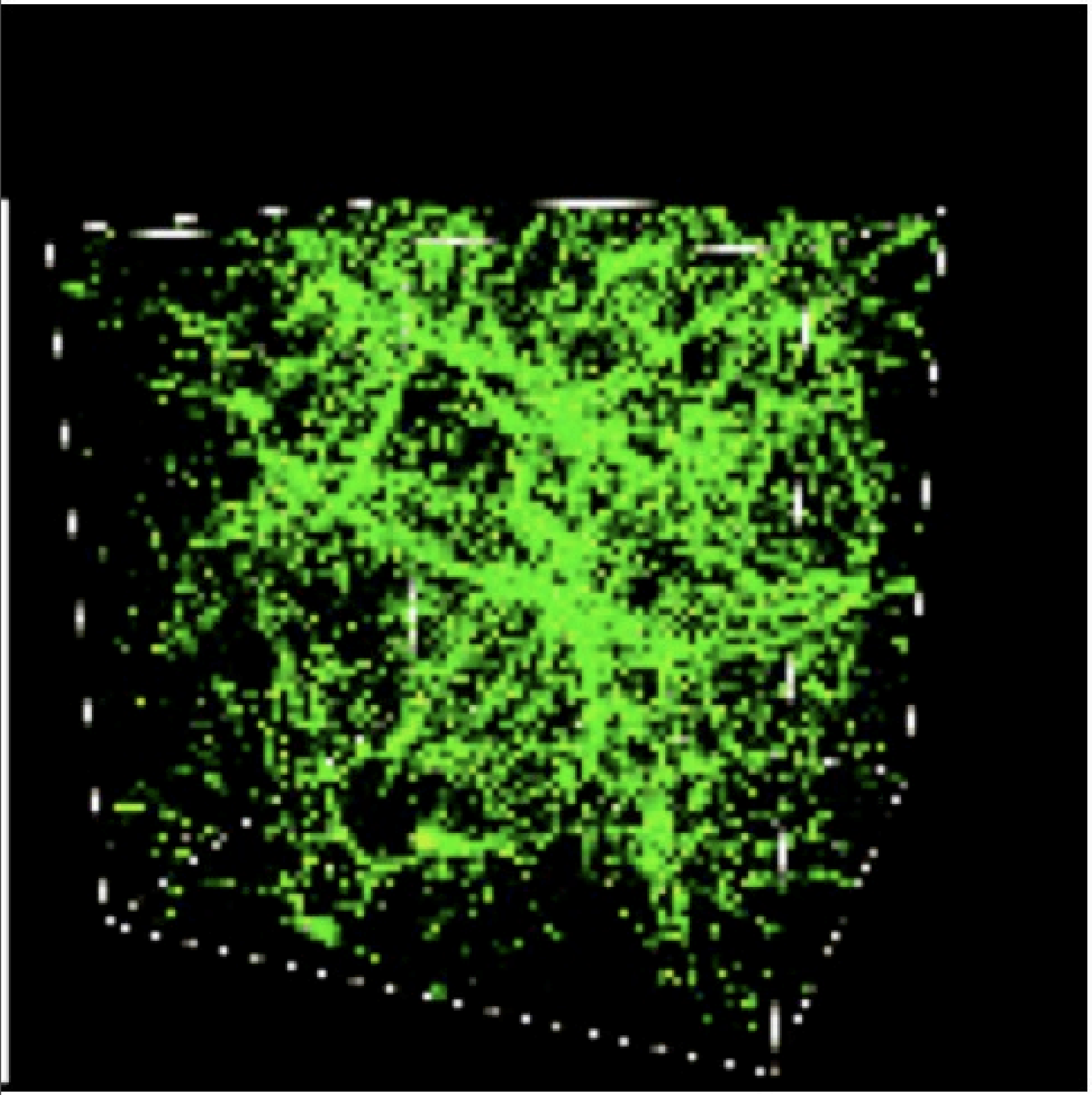
Connection to IR Cirrus?

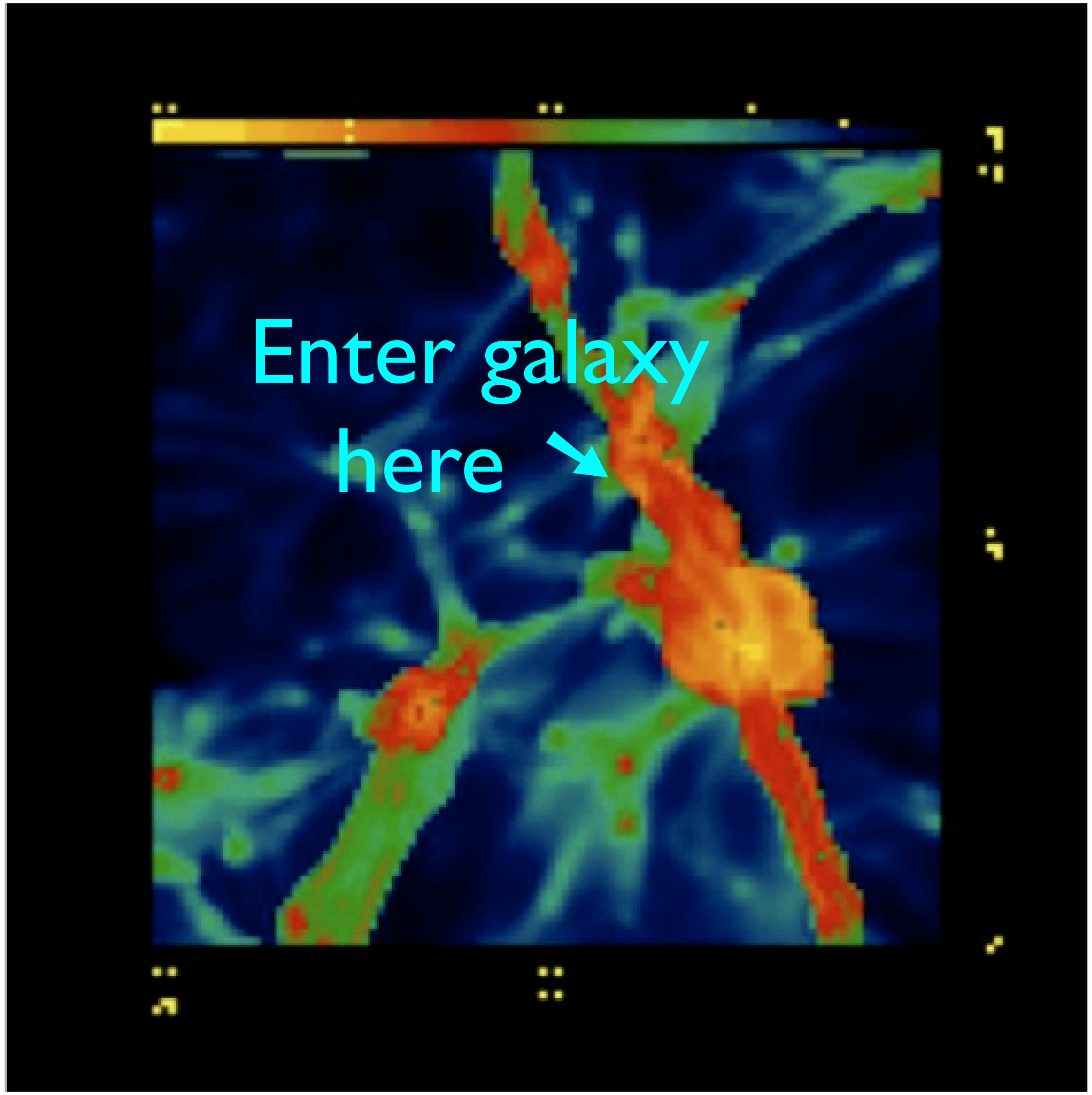
10^8 M_{sun} in gas


Large galaxy
Metal-polluted regions
IGM at z = 0.1

WHIM in the Cosmic Web

Cen & Ostriker (2006) simulations





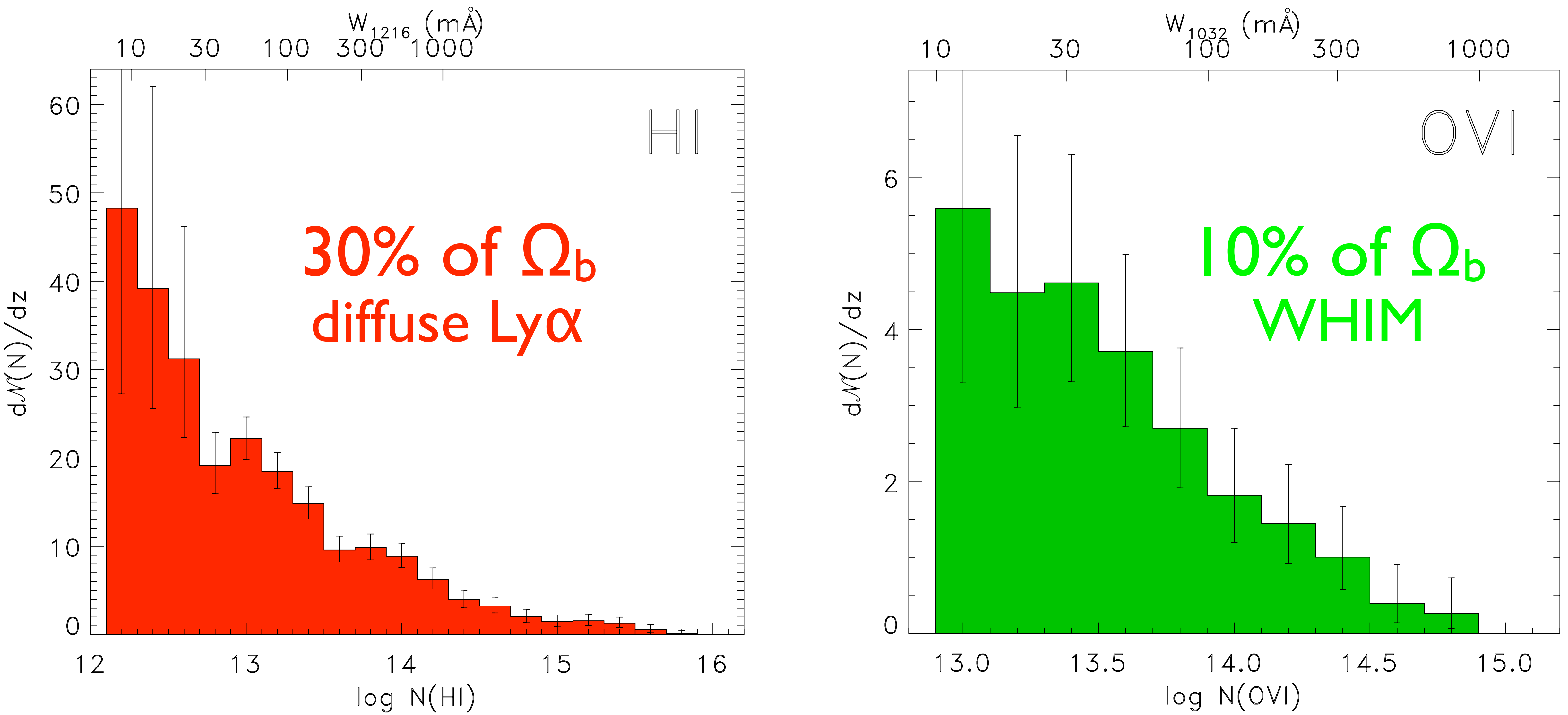
Shock-heated Gas at 10^5 - 10^7 K

FUSE/HST Survey

7 km/s (HST)
20 km/s (FUSE)

(Danforth & Shull 2008, ApJ, 679, 194

- 28 AGN with known Lyα absorbers (STIS/E140M)
- Measured absorbers in hydrogen Lyman series, plus five metals [O VI, C III, Si III, Fe III, N V, C IV, Si IV]
  - $z < 0.4$ for Lyman lines (650 absorbers)
  - $z < 0.2$ for C III 977Å (found 39 systems)
  - $z < 0.4$ for O VI 1032, 1038Å (found 83 systems)
  - $z < 0.4$ for Si III 1206 (found 53 systems)



$\mathcal{N}$=650, β=1.73±0.04

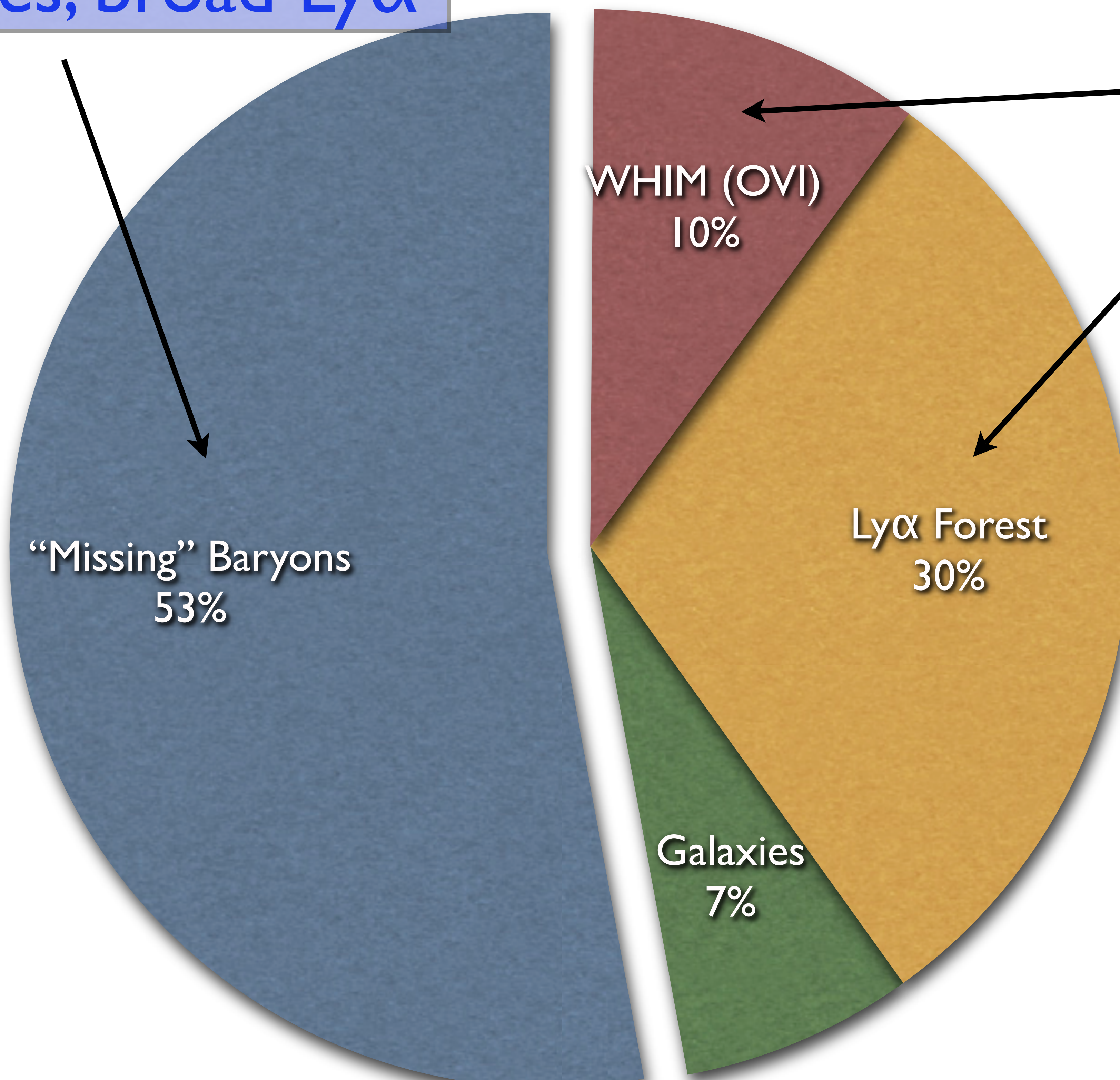
$\mathcal{N}$=83, β=1.98±0.11

Danforth & Shull 2008, ApJ, 679, 194

Baryon Census (low-z)

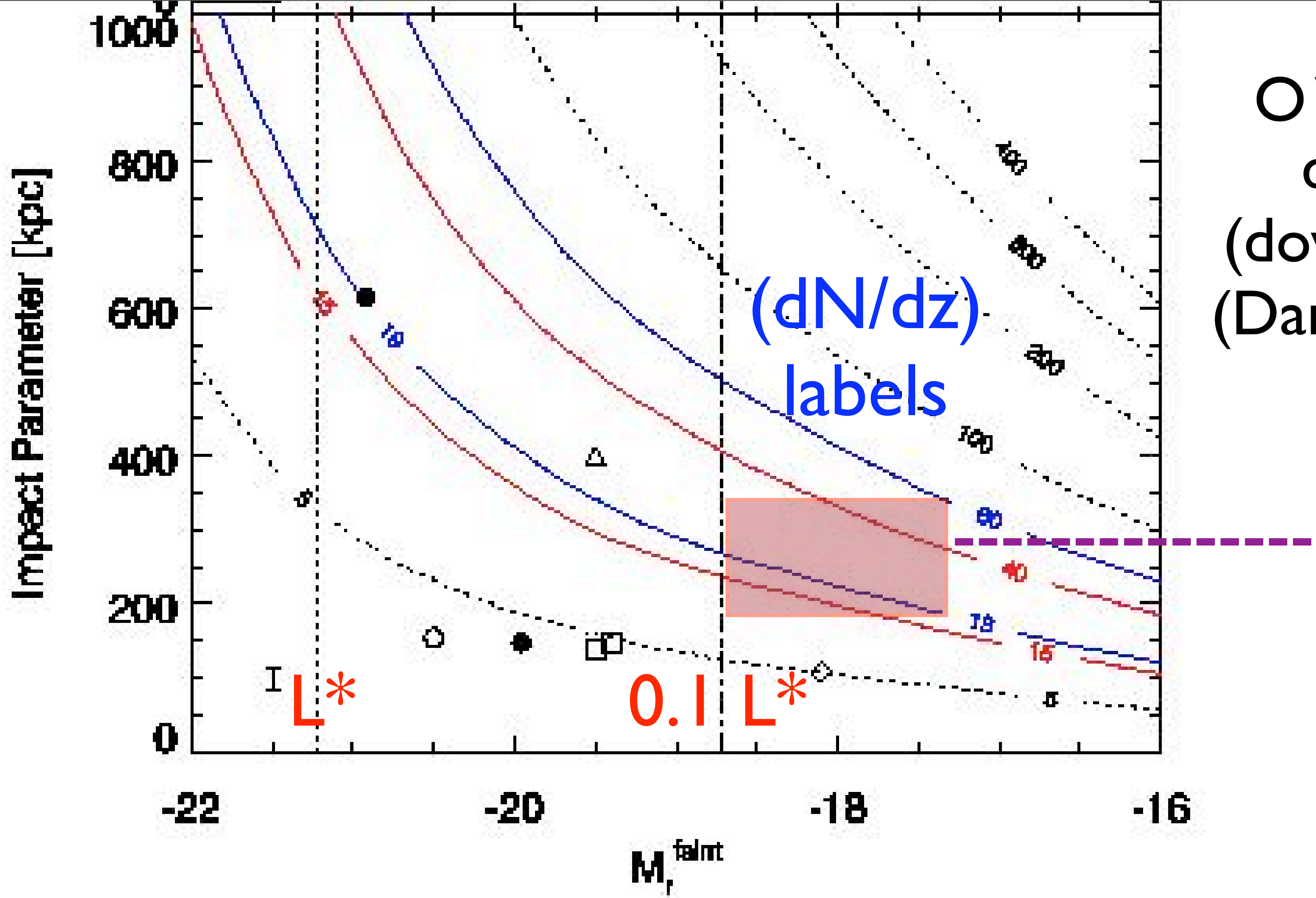
Probed by X-ray lines, broad Lyα

Both of these are uncertain



IGM Systematics:

- EUV radiation field
- Oxygen metallicity
- Ioniz corrections
- Cloud geometry



O VI absorbers
dN/dz ≈ 40
(down to 10 mA)
(Danforth & Shull)

$(dN/dz)_{OVI}$ ⇒ Absorber size

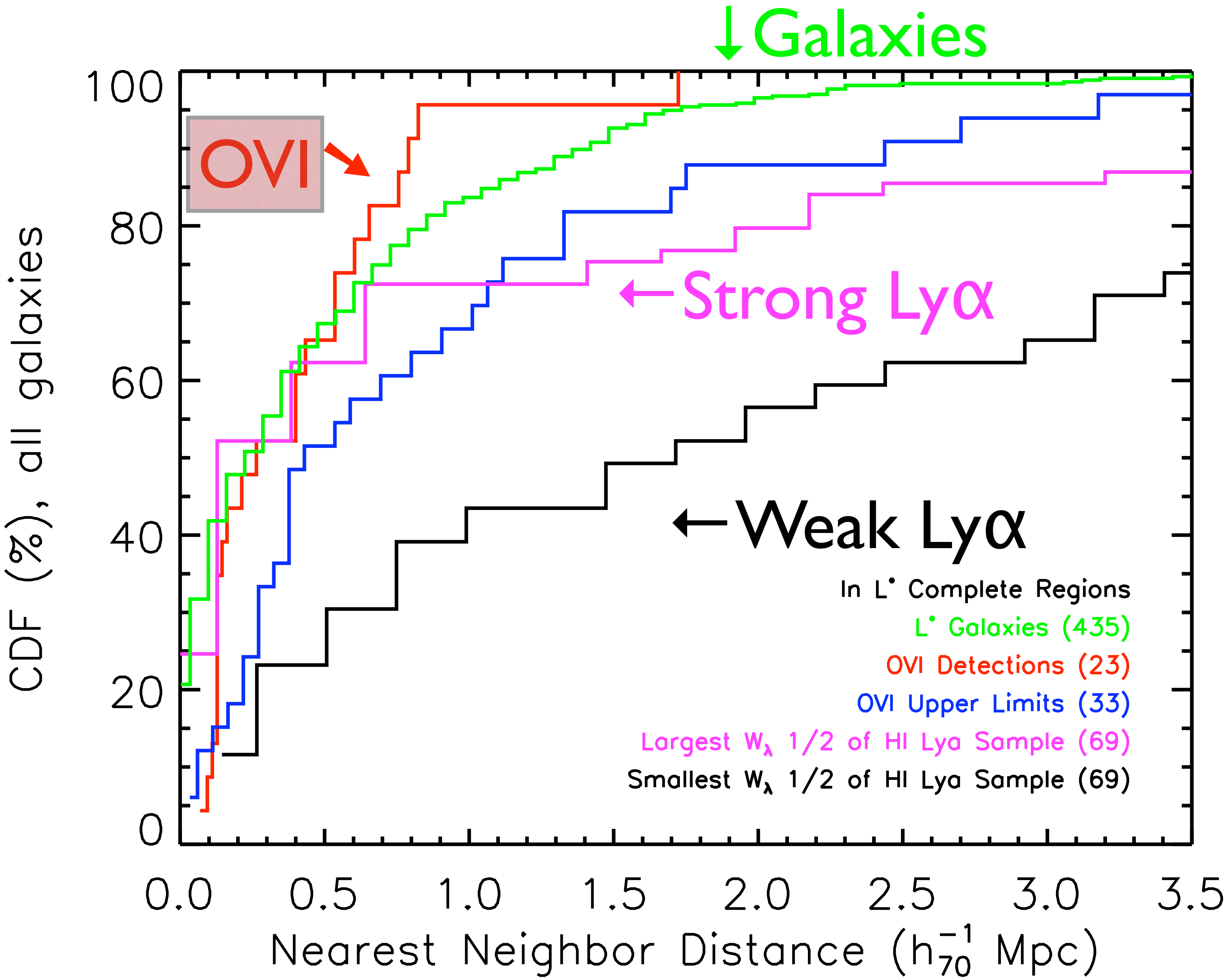
(tied to SDSS galaxies)

Dwarf galaxies
R ≈ 200-300 kpc
(0.03-0.1 L*)

Nearest-galaxy distributions

Stocke et al. (2006)

OVI absorbers track galaxies:



O VI absorbers lie within 800 kpc of L* galaxies

& within 200 kpc of 0.1 L* galaxies

Summary of Results:

1) We have accounted for ~50% of the baryons

- 10% in collapsed structures (galaxies, clusters)
- 30% in warm (10^4 K) photoionized gas (Lyα)
- 10% in hot ($10^{5.5}$ K) gas (O VI ultraviolet lines)

Other 50% may be in even hotter (10^6 K) gas

2) The hot (O VI) gas is close to galaxies, and thus is a reservoir for low-Z gas infall

- Within 200 kpc of 0.1 L^* galaxies (outflows?)
- Cooling ⇒ 0.1 M_{sun}/yr infall to halos?

What's Next ?

20x STIS (UV spectra
at 15 km/s resolution

- Hubble SM4 (Oct 2008: Cosmic Origins Spectrograph)
- Perhaps a restoration of STIS (UV echelle spectra)
- OVII, OVIII, NVI, CV, CVI, NeIX from Con-X (2020?)
- Next-generation large (6-10m) UV/O space telescope?
- Theory: hot/cold gas interfaces, non-equilib.

COS-GTO Studies of IGM
(253 orbits)

$\Delta z \approx 10$ pathlength

Large-Scale Structure in Baryons .... 100 orbits 18 QSOs

Cloud sizes, Lyα, metal lines, blazars (broad Lyα absorbers), starburst wind outflows, galaxy halos, high-velocity clouds

WHIM in Cosmic Web and Halos .... 100 orbits 17 QSOs

High ions (O IV/V/VI, N V, C IV), BLAs, survey redshifts z out to 0.67

Great Wall Tomography .... 19 orbits, 4 QSOs

He II Reionization Epoch .... 27 orbits, 4 AGN

(4 AGN at z = 2.7-3.2)

HST/COS Community Legacy Project?

QSO Absorption-Lines: $\Delta z \approx 40$ pathlength

500 orbits, 140 AGN (R = 20,000, S/N = 30)

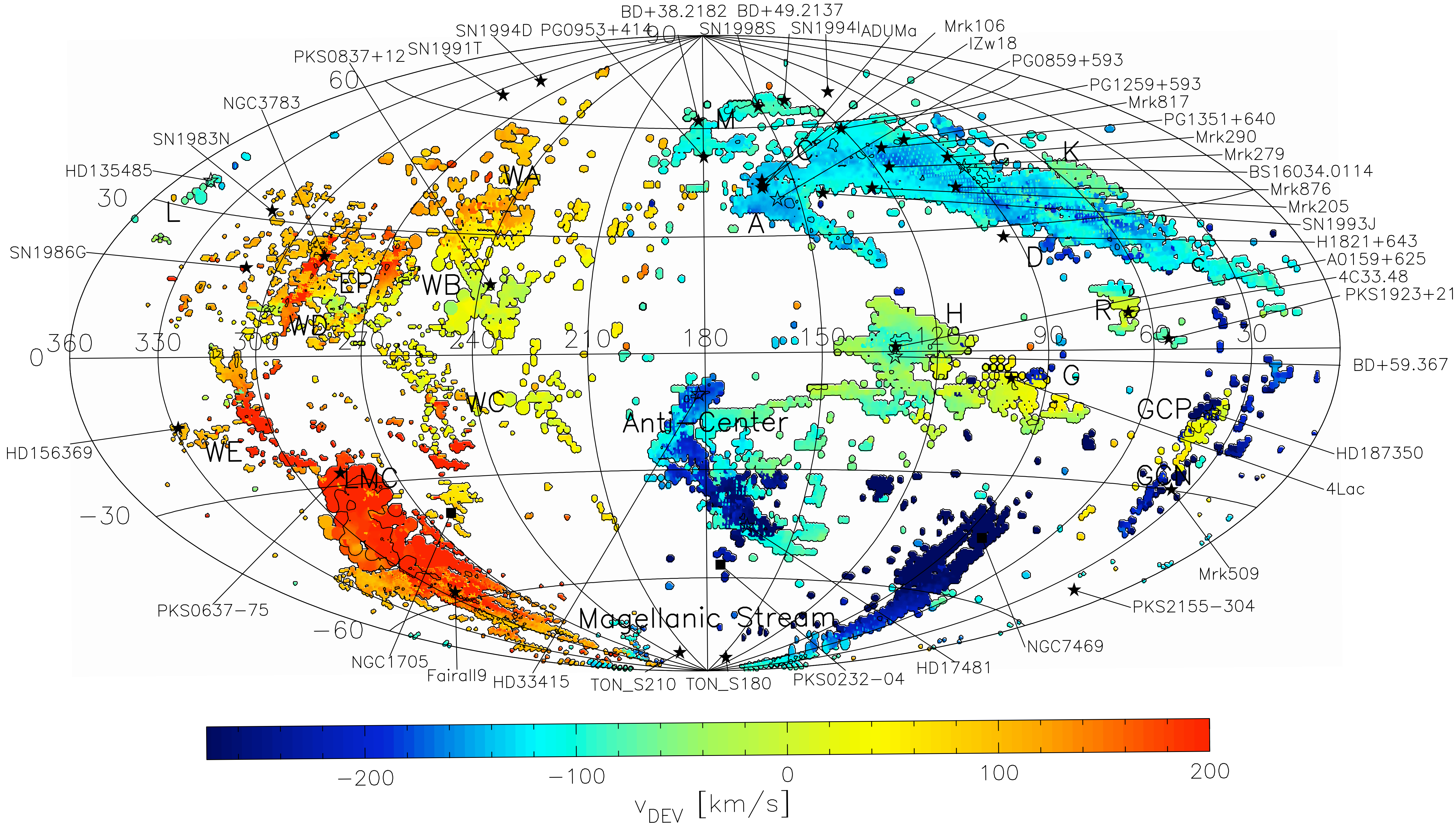
- IGM Large-Scale Structure ("Cosmic Web")
- Multiphase IGM and ISM (including WHIM)
- IGM metallicity (content, evolution, transport)
- Chemical extent of galactic halos & winds
- Feedback (energy, radiation, metals) to IGM
- Galactic high-velocity clouds, AGN outflows

Such proposals will be accepted for HST Cycles 18-20
Director Discretionary Time added for Treasury Programs

Topic #2: High Velocity Clouds

HST/FUSE sightlines

Wakker (2003) HVC overlay



Temperature of MW Halo Gas

$$T_{gas} \approx (m_H\, \sigma^2/3k_B) \approx (2\times10^6\ \mathrm{K})(\sigma_v/220\ \mathrm{km/s})^2$$

Or, the (cosmological) halo virial temperature:

$$T_{vir} = (2\times10^6\ \mathrm{K})\ (M_{12})^{2/3}\ (\Omega_m h^2/0.13)^{1/3}\ [(1+z_{vir})/4]$$

Assumes: $\rho_{vir} \approx 178\ \Omega_m \rho_{crit}$ $\quad kT_{vir} \approx (GM_{vir}\, m_H/R_{vir})$

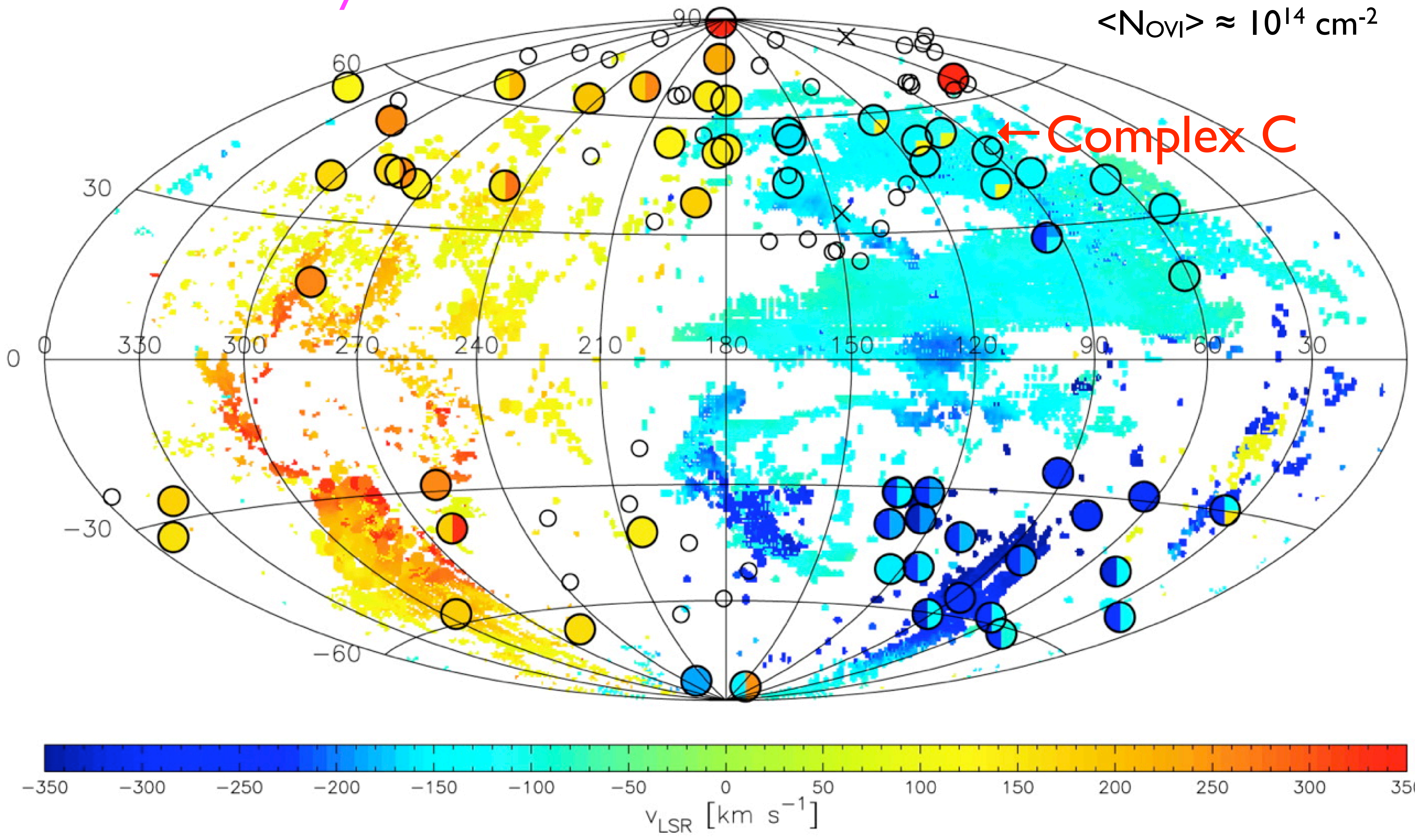
$M_{vir} = (4\pi/3)\ \rho_{vir}\ (R_{vir})^3$ $\quad \rho_{crit,0} = (3H_o^2/8\pi G)$

(and $z_{vir} \approx 3$)

O VI (HVCs)

Sembach et al. (2003)
FUSE survey

Coverage ≈ 60-80%



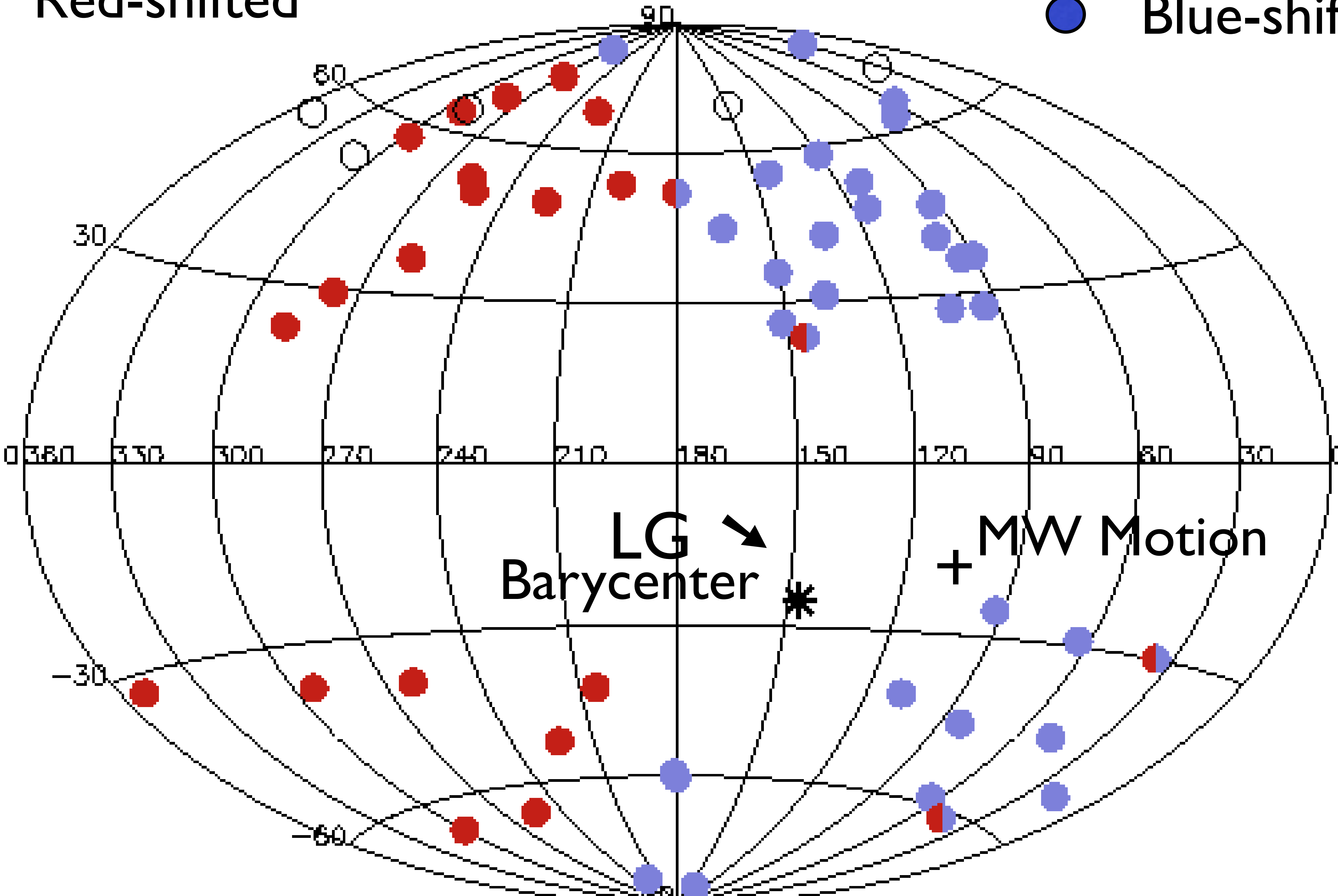
Si III (HVCs)

Collins, Shull, & Giroux (2008)

Coverage ≈ 90%

Red-shifted

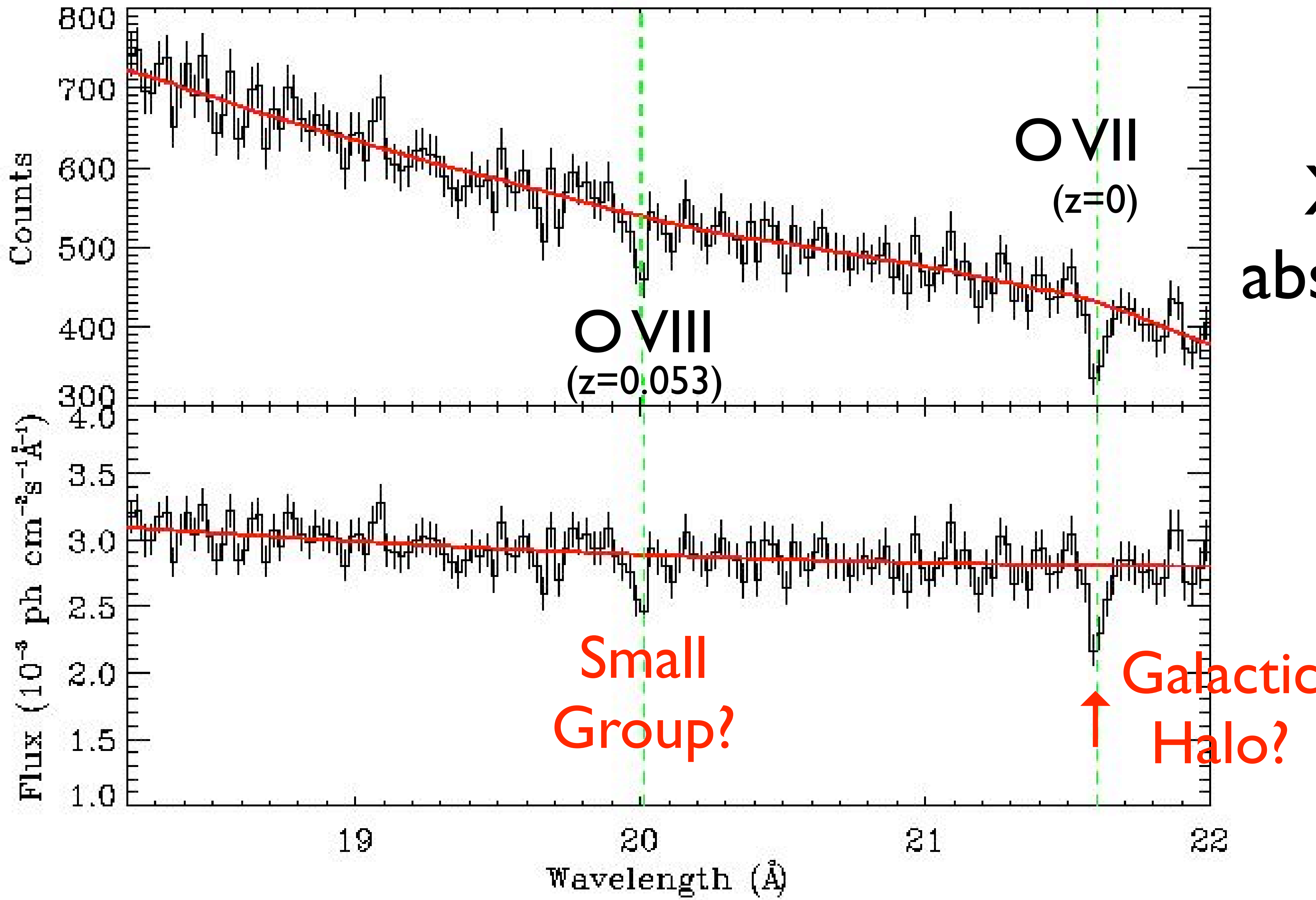
Blue-shifted



X-ray Absorption (O VI, O VIII) - Chandra

PKS 2155-304 Sightline

[Fang, Canizares, & Yao 2007]



X-ray absorbers

Mass Estimates (Hot Gas near Galaxy)

$$M_{hot} \approx (4\pi R^2)\ [N_{OVII}\ (1.32 m_H)/(5\times10^{-4})\ Z_O\ f_{OVII}\ ]$$

$$\approx (1.3\times10^{13}\ M_{sun})\ (R_{Mpc})^2\ (N_{16})\ (0.2\ Z_{sun}\ /Z_O)(f_{OVII})^{-1}$$

plus dark matter on Mpc scales?

Cannot exceed 20% mass of the Local Group

$(M_{LG} \approx 2\times10^{12}\ M_{sun}) \Rightarrow R_{hot} \leq 175$ kpc

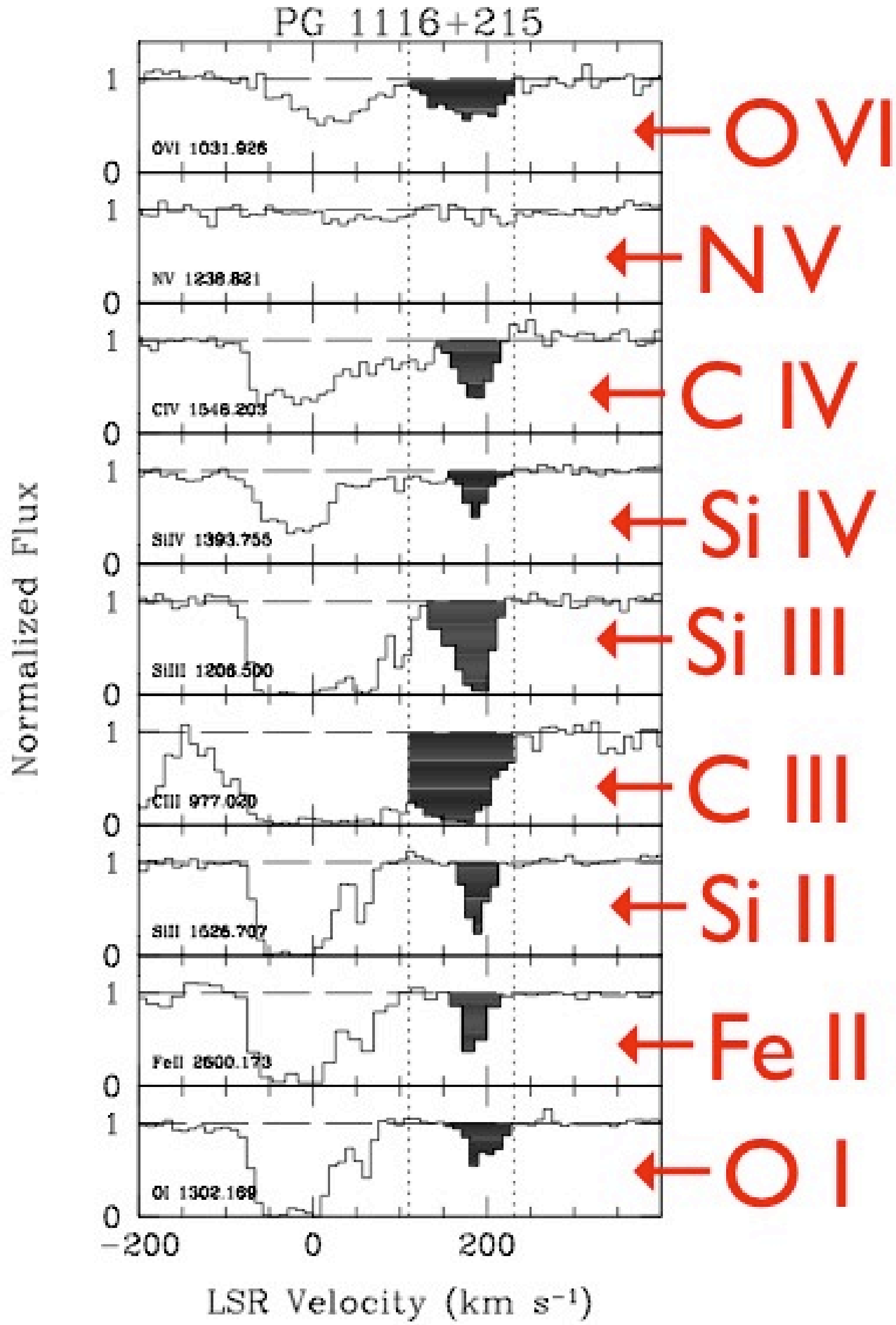
Hot-gas mass is probably $\sim 10^9\ M_{sun}$

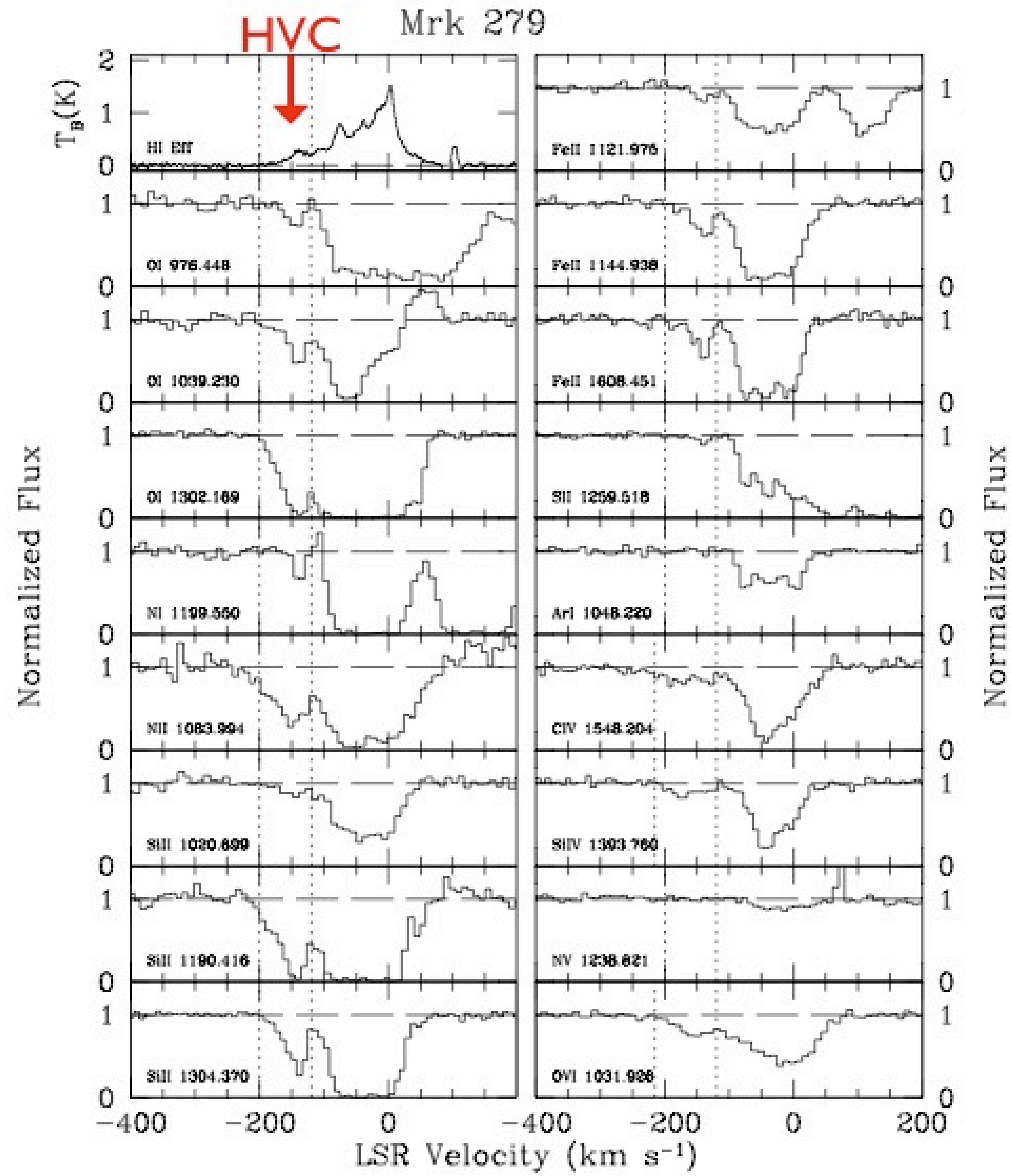
(Distributed as exponential-halo - 50 kpc scale height)

Assume: $N_{OVII} \approx (10^{16}\ \mathrm{cm}^{-2})\ N_{16}$, $R_{hot} \approx (1\ \mathrm{Mpc})\ R_{Mpc}$

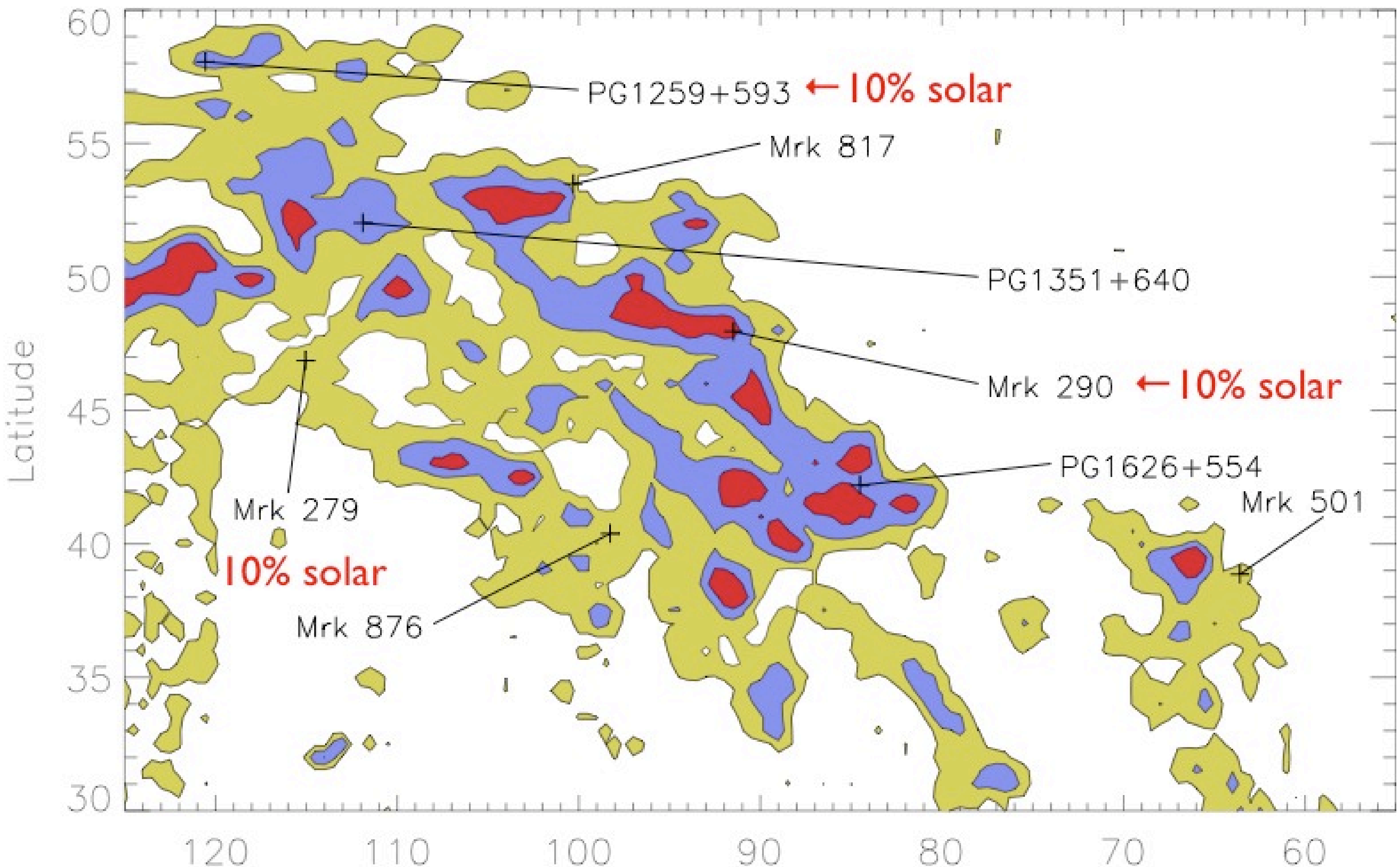
Metallicity $Z_O \approx 20\%$ solar, $f_{OVII} \approx 0.40\text{-}0.98$

“Highly Ionized HVCs” - with low ions too! (Collins, Shull, & Giroux 2005, 2006 ApJ)





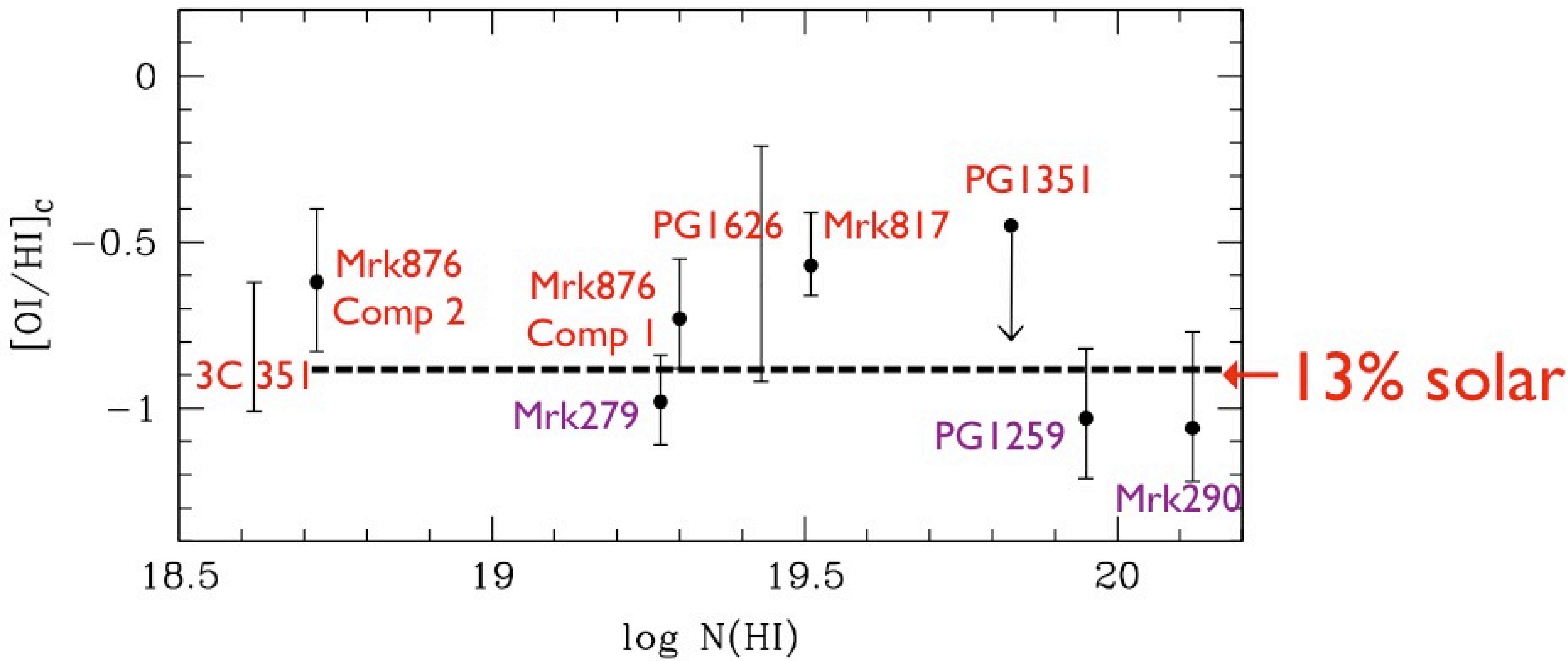
Low ions (O I, C II, Si II, Fe II) along with O VI



Complex C -- 11 sightlines (HST/FUSE)
[Collins, Shull, & Giroux 2003, 2007]

[O/H] ranges from 10-30% solar

Very little trend of (O/H) with N_{HI}



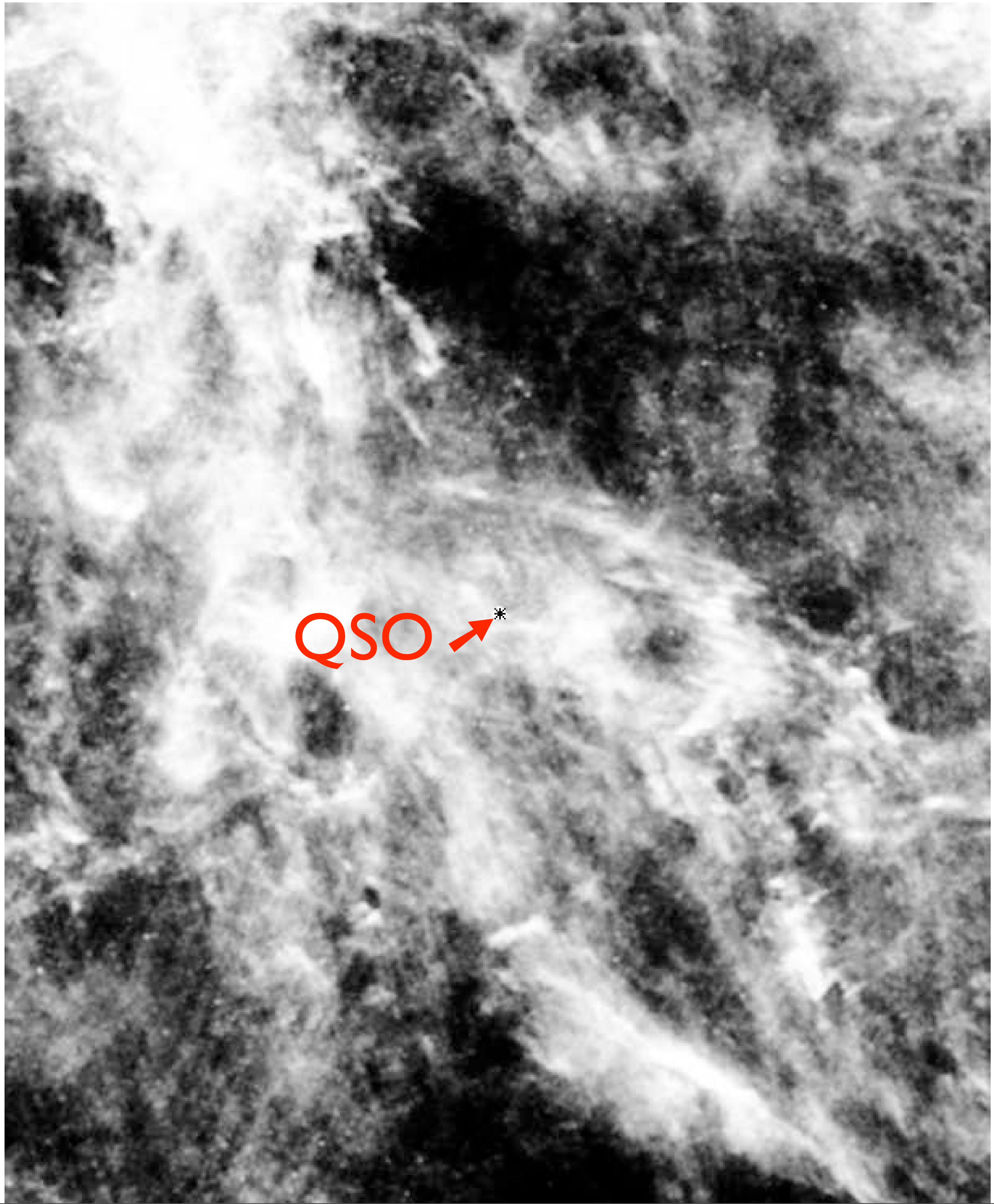
Complex C -- (O/H) Metallicities
Range from 10-30% Z_{sun} in [O I/H I]

Collins, Shull, & Giroux 2007 ApJ, 657, 271
(9 HVCs along 8 AGN sightlines)

InfraRed Cirrus

MSX

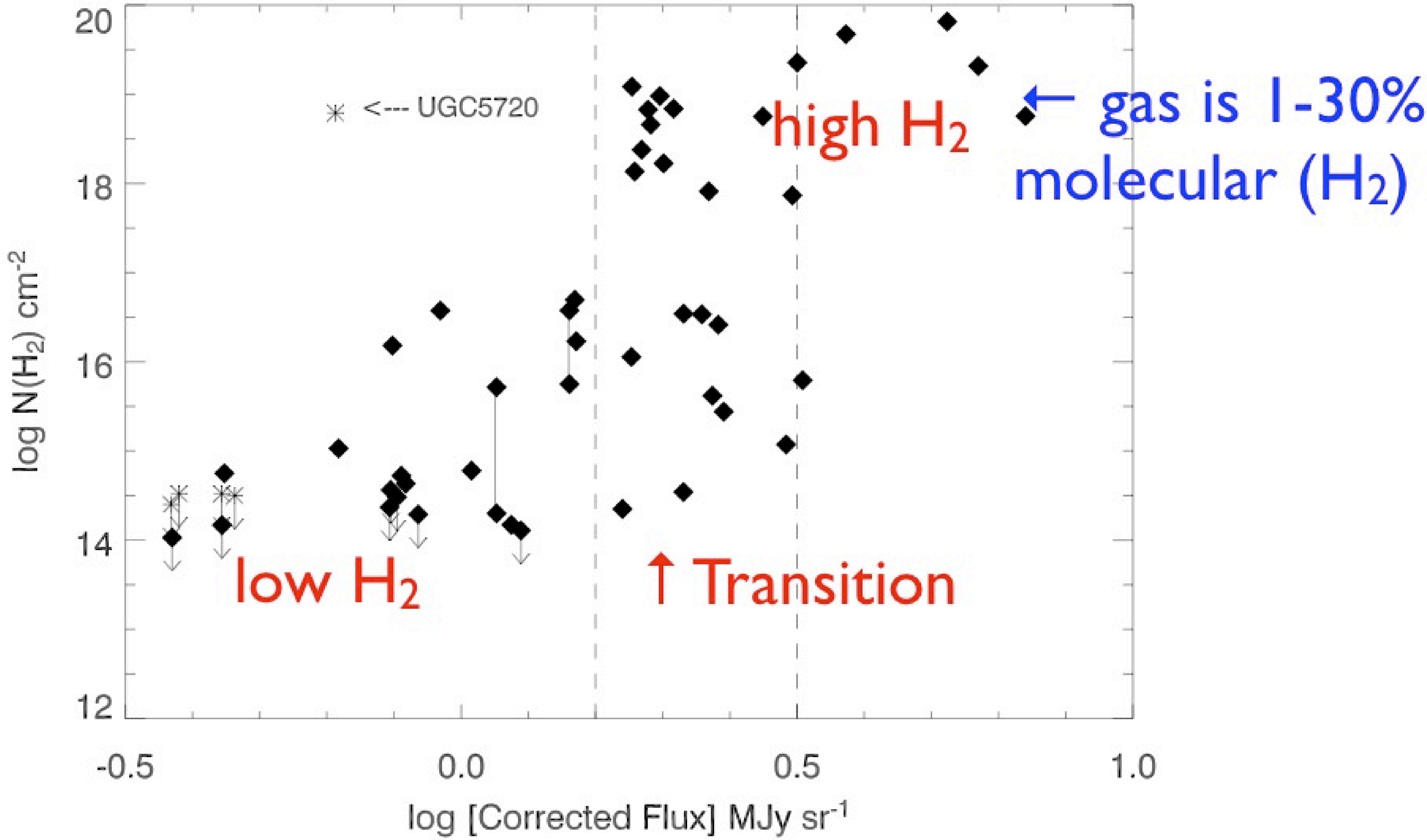
InfraRed Legacy



Cooler Gas ?

A quasar behind 100 μm IR cirrus (one of 45 studied with FUSE in H_2)

Gillmon & Shull (2006) ApJ



Transition in H_2 seen in IR Cirrus
(2-3 MJy/sr or $N_H \approx 10^{20.4}$ cm^{-2})

Estimated Mass in IR Cirrus and H2 Gas

Very rough estimates (Gillmon/Shull 2006)

$M_{H2} \approx 3000\ M_{sun}$ (local cone, b > 30°)

$M_{H2} \approx 10^7\ M_{sun}$ (above entire disk)

$M_{gas} \approx 10^8\ M_{sun}$ (above entire disk)

These estimates are made by integrating f_{H2} and N_{HI} over the 100 μm cirrus template (NGP).

Where did gas and metals come from?

What is the lifetime of the cirrus?

Could the cirrus come from cooling halo gas?

$M_{hot} \approx (2\text{-}10)\times 10^7 \ M_{sun}$ (from O VI & O VII in halo)

$t_{cool} \approx (2 \text{ Gyr}) \, [T_6 \,/\, n_{-4} \, \Lambda_{-22.5}]$ (cooling at 20% Z_{sun})

The cooling time will decrease
as temperature drops below 10^6 K
(peak cooling rate is at 300,000 K)

$$(dM/dt)_{hot} \approx (M_{hot}/t_{cool})$$
$$\approx (0.05 \ M_{sun} \ yr^{-1})[n_{-4} \, \Lambda_{-22.5} \,/\, T_6]$$

$\Rightarrow$Will accumulate $5\times 10^7 \ M_{sun}$ per Gyr

(comparable to M_{cirrus})

Summary

- Much of the halo and infalling HVCs have metallicities of 10-30% solar (Complex C mass-weighted mean is 13% solar).

- Hot halo gas (O VI and O VII) exists kinematically with cooler photoionized gas within 50-100 kpc. Reservoir 10^9 M_{sun}. The HVCs are clumps of cooling gas, falling through hot halo, with conductive interfaces, shocks, and turbulent mixing layers.

- The Galactic thick disk contains ~10^8 M_{sun} of H_2-bearing cirrus. The halo contains >10^8 M_{sun} of hot gas (10^5 - 10^6 K).

Some cooling halo gas could end up in the thick disk (IR cirrus), mixed with dust and metals from the disk